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Title: Isentropic Compression Studies at the Los Alamos National High Magnetic Field Laboratory

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Isentropic Compression Studies at the Los Alamos National High Magnetic Field Laboratory.

Douglas G. Tasker, Charles H. Mielke, George Rodriguez, Dwight G. Rickel

For presentation at 18th International Pulsed Power Conference, Chicago, Illinois, June 19 to June 23, 2011.

We demonstrate that the established pulsed power infrastructure at the National High Magnetic Field Laboratory – Pulsed Field Facility (NHMFL-PFF) at the Los Alamos National Laboratory can be adapted to obtain high quality isentropic compression experiment (ICE) data on materials in extreme conditions of dynamic high pressure.

Experiments utilized a single-turn magnet pulsed power system at the NHMFL-PFF that was originally designed to measure actinide samples in extremes of high magnetic field (to 300 Tesla) [1, 2]. A simple modification to the single-turn magnet has converted it to a fast turnaround dynamic high pressure measurement system. This paper details the work done including important background details that indicate that much more can be accomplished with optimization of the load characteristics in terms of ultimate peak pressures. To match the rise time of the NHMFL capacitor bank (~2 µs versus ~0.5 µs for the Sandia Z-machine[3]) the sample dimensions can be relatively large, i.e., up to 5 mm thickness. The maximum stresses are ~50GPa (0.5 Mbar) at the maximum bank voltage (60 kV) and higher pressures may be possible if the sample is tamped.

For the design and predictions of performance of the NHMFL-ICE experiment it is important to have good predictive models. A SPICE code simulation was chosen to model all aspects of the experiment, electrical and physical. To this end, accurate dynamic load models were developed to simulate the compression and expansion of the dynamic load at high pressures using shock physics principles.

A series experiments have been performed which demonstrated the feasibility of the NHMFL-ICE technique. The results will be shown and discussed.

The NHMFL-ICE technique is an excellent method for measuring equations of state (EOS) at megabar pressures. Because a complete EOS can be obtained in one experiment from zero to the peak pressure, and because many shots can be fired in one day, the technique promises to provide high quality EOS data at relatively low cost.

[1] S. E. Sebastian, *et al.*, "Metal-insulator quantum critical point beneath the high Tc superconducting dome," *Proceedings of the National Academy of Sciences,* vol. 107, pp. 6175-6179, April 6, 2010.

[2] A. M. Alsmadi, *et al.*, "Complex conductivity of UTX compounds in high magnetic fields," *Journal of Applied Physics,* vol. 105, pp. 07E108-3.

[3] C. Deeney, J. P. Davis, C. A. Hall, M. D. Knudson, and T. J. Vogler, "High-Pressure Isentropic Compression Experiments on the Sandia Z Accelerator," in *Plasma Science, 2005. ICOPS '05. IEEE Conference Record - Abstracts. IEEE International Conference on*, 2005, pp. 103-103.

Isentropic compression studies at the Los Alamos National High Magnetic Field Laboratory

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George Rodriguez, and Dwight Rickel

Los Alamos National Laboratory

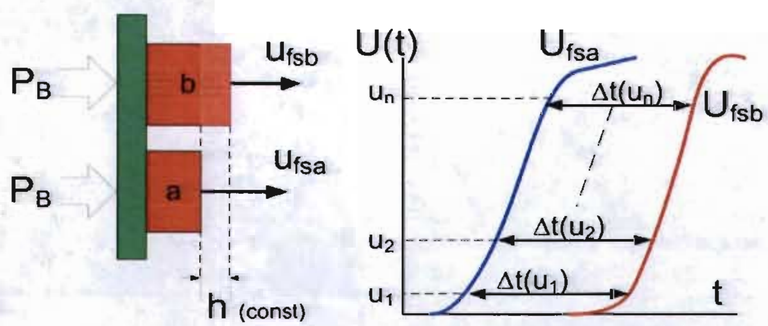
IEEE PPC 2011, Chicago

Introduction

- **Recent ICE experiments performed on the Sandia Z-machine and elsewhere are providing our nation with isentropic Equation of State data in extreme dynamic high stress environments.**
- **The National High Magnetic Field Laboratory (NHMFL) can offer a simple ICE experiment at relatively high stress (up to ~1Mbar) with a high sample throughput and relatively low cost.**
  - Feasibility demonstrated in Sept 2010 experiments
- **We will:**
  - Discuss the physics of the NHMFL-ICE experiments
  - Predict the likely performance space
  - Present data from the first <u>proof-of-principle</u> experiments

What is ICE?

- **ICE experiment uses smoothly rising magnetic fields to compress materials to large stresses**
  - Ramp gives isentropic compression (no shock)
  - Material response to all stresses from 0 to peak acquired in one experiment
  - Phase changes can be studied
- **Identical (different thickness) samples are placed on the rear surfaces parallel conductors**
  - Two samples, with a difference in thickness of *h*, are **compressed by *identical* magnetic forces**. Laser velocimetry used to measure the surface velocity profiles, $U_{fs}(t)$, at the rear surfaces.
  - Wave speed $c_L(u)$ measured for the waves to travel a distance *h* at each value of *u(t)* in time
  - Result: continuous plots of c_L and stress σ as functions of particle velocity *u.*

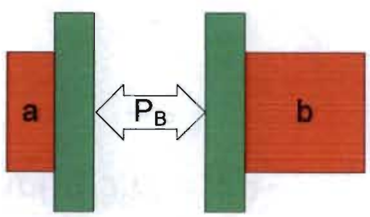


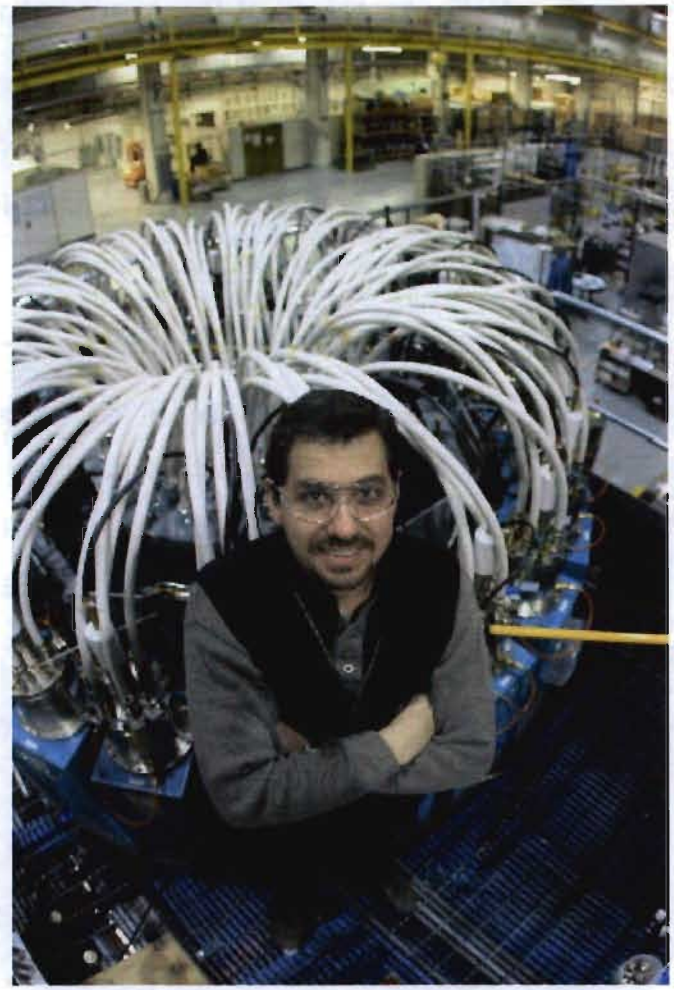
$$c_L(u) = \frac{h}{\Delta t(u)} \qquad d\sigma = \rho_0 c_L(u) du$$

Exact

Simple NHMFL-ICE POP experiments

- Triangular plate and load "coil" pressed to shape as parallel plate load
  - Not an ideal design, but OK for proof-of-principle experiments
  - Connected directly to 144-µF, 60-kV capacitor bank
    - No transmission plates, vacuum insulation, etc.



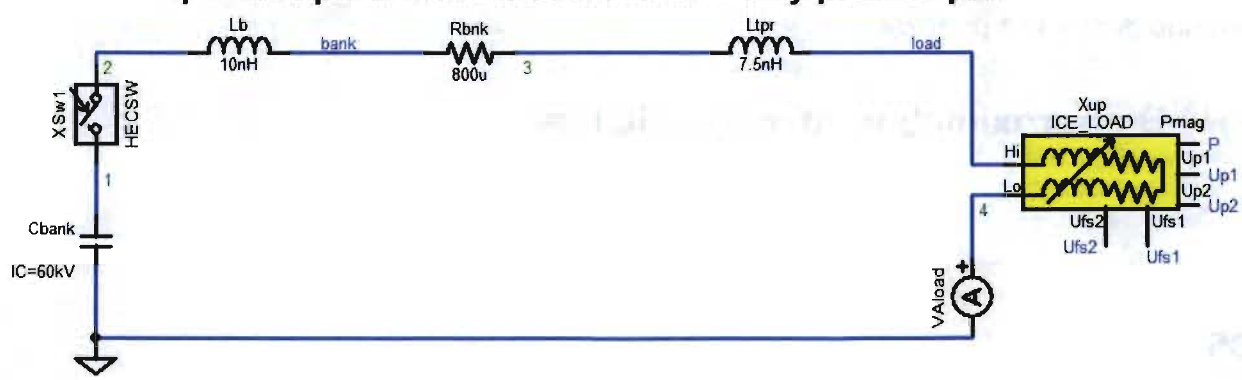


spICE analysis of circuit

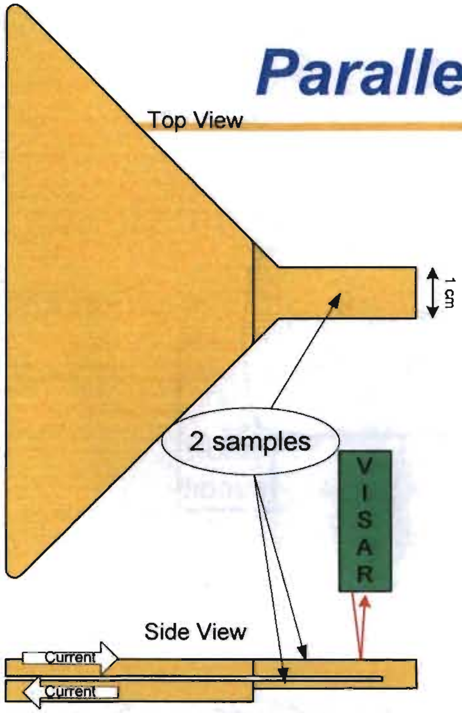
- **For experimental design and subsequent data analysis it is important to have good predictive models of the system performance.**
  - We chose to use the SPICE circuit code to simulate all aspects of the experiment, electrical AND physical
- **For the NHMFL-ICE circuit this is not straightforward.**
  - The capacitor bank and closing switches may be modeled by simple circuit parameters
  - BUT the load is a complex system dominated by the dynamics (shock physics) of the materials
- **The load is *time dependent* and *current dependent***
  - Accurate dynamic load models had to be developed to simulate the compression and expansion of the load from shock physics principles
- **Uses 1½-D approximation to magnetic load**

spICE circuit simulation for NHMFL

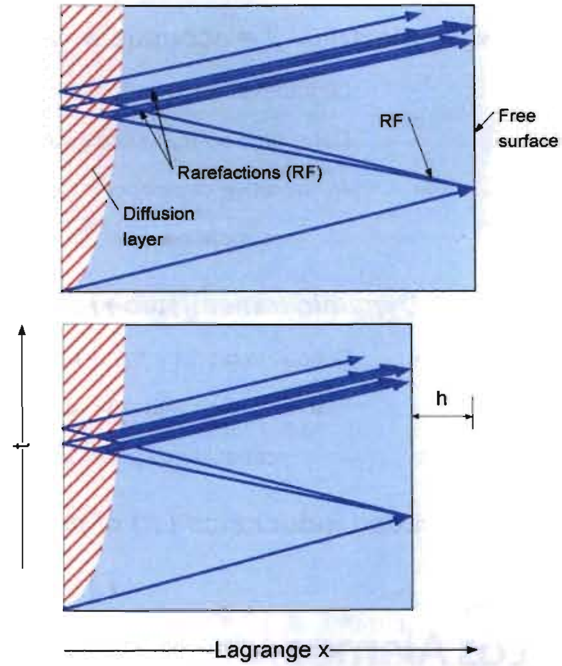
- **Predictive tool – <u>not used</u> for data analysis**
- **Dynamic components (in yellow): Xup is the load simulation circuit**
- **Static components:**
  - C, Lb and Rbnk are the capacitance (144 μF) inductance and resistance of the capacitor bank, its cables and connections between the bank. Ltpr is the inductance of the load taper
    - At 60 kV, energy = 260 kJ (equivalent to ~40 g explosive)
- **Output values:**
  - U_{p1} and U_{p2} are the interior particle velocities, U_{fs1} and U_{fs2} are the surface velocities
  - P_{mag} is the magnetic stress common to both samples
- **Have models for both parallel plate and coaxial loads – only parallel plates shown here**



Parallel plate load compression and expansion



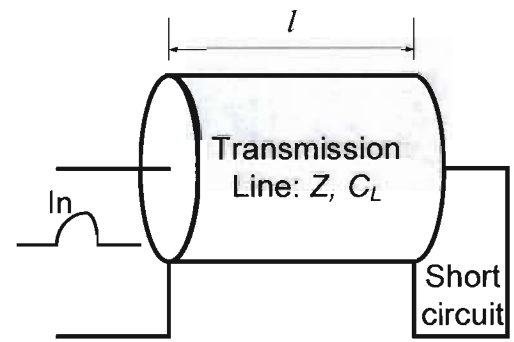
- **Inner plate separation *d(t)* increases with time**
  - So must calculate velocities of inner surfaces (Up)
- **Inductance increases with *d(t)***
- **Rarefactions from outer surfaces accelerate separation when they return to inner surfaces**
- **<u>Wave velocities are pressure dependent</u>**

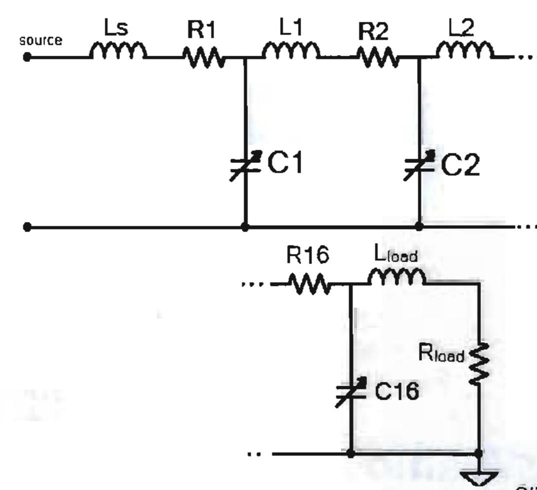


Load model transmission line analog

- **Wave propagation and reflection in the expanding electrodes were modeled in an electromechanical analog**
  - Mechanical particle velocity = electrical current
  - Mechanical pressure = electrical voltage
- **Load with free surface treated as a short-circuited transmission line**
  - Cannot yet handle effects of diffusion layer
- **Electrical Z = acoustic wave impedance of the load = $\rho_0 c_L$**
  - Lagrangian wave speed, c_L ; initial density, ρ_0
  - Delay time = l / c_L where l is length
  - As the wave velocity $c_L = c_L(P)$ - function of pressure
    - c_L increases with time during the ICE experiment
- ***Dynamic transmission line***
  - Difficult to model - many models proved to be numerically unstable
  - Stable solution with a 16-staged lumped RCL circuit model for the transmission line
    - capacitance per stage $C = C(pressure)$, *i.e.*, a function of V (pressure)
- **Load inductance *L(t) of parallel plates solved analytically***

$$L(t) = \mu_0 K l \times \left(d(t) / W \right)$$

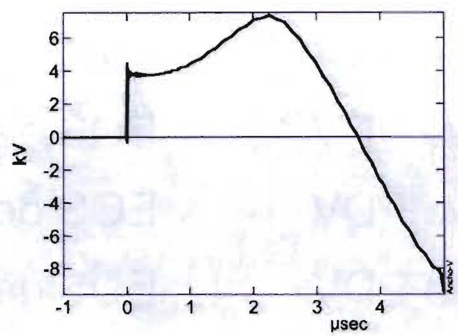




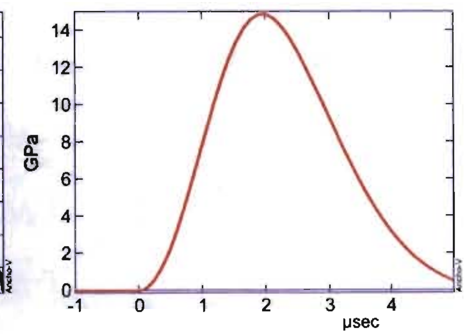
spICE predictions of NHMFL-ICE load response

- **Copper samples 77 and 125 mil**
- **Bank here charged to 35 kV**
- **PDV data obtained in POP experiment**
- **Effective end of experiment when first relief waves arrived back at the thin sample surface**
  - Will see the experimental results in a moment
- **Notice that for this calculation relief waves limit the EOS experiment to a peak stress at ~1.5 μs whereas the current peaks at 2.3 μs**

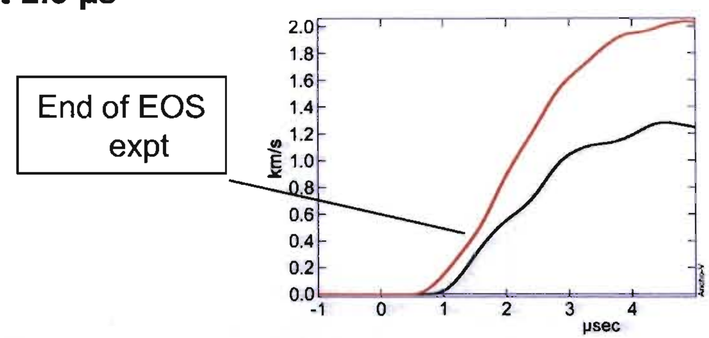
Load voltages, kV



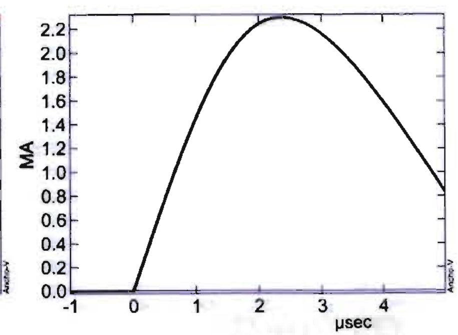
Load stress, GPa



Surface velocities, km/s



Load current, MA



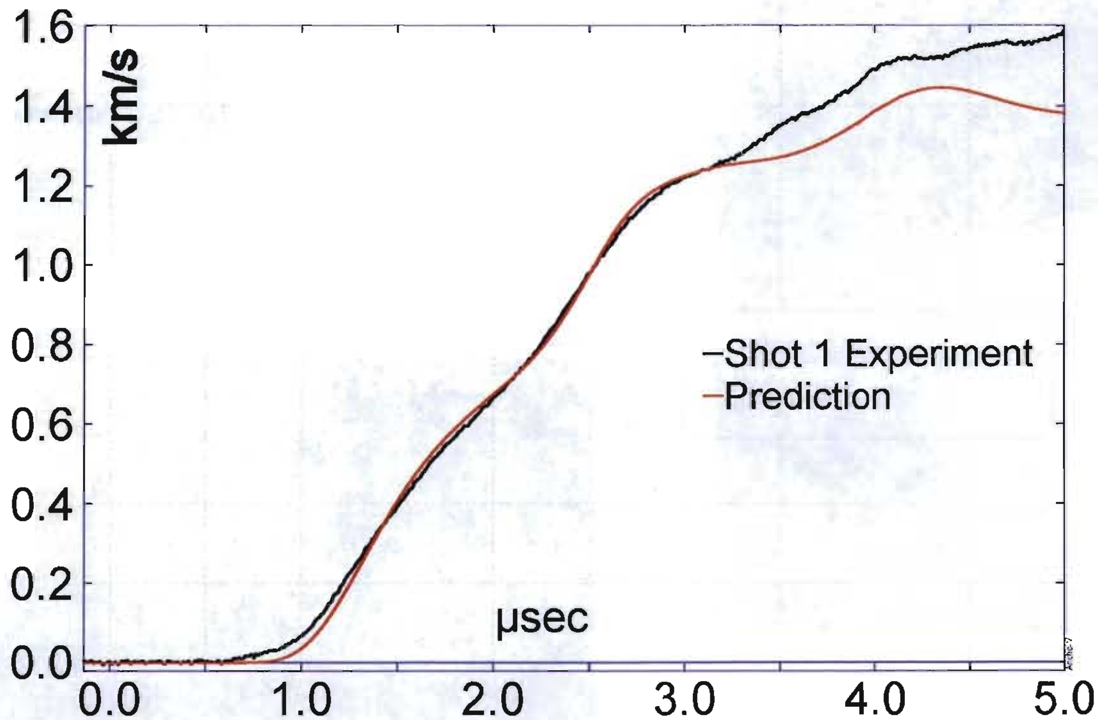
POP experiments -Sept 2010

1	Copper	One VISAR	Proof-of-principle	Good data
2	Copper	One VISAR	Proof-of-principle	Good data
3	Copper	Two PDV	EOS demo	Good data
4	Tantalum	Two PDV	EOS demo	Single-can misfire
5	Tungsten	Two PDV	EOS demo	Good data

September 2010 experiments – before and after

- **PDV gauges situated above and below the load**
  - Detected velocities of the two tungsten samples

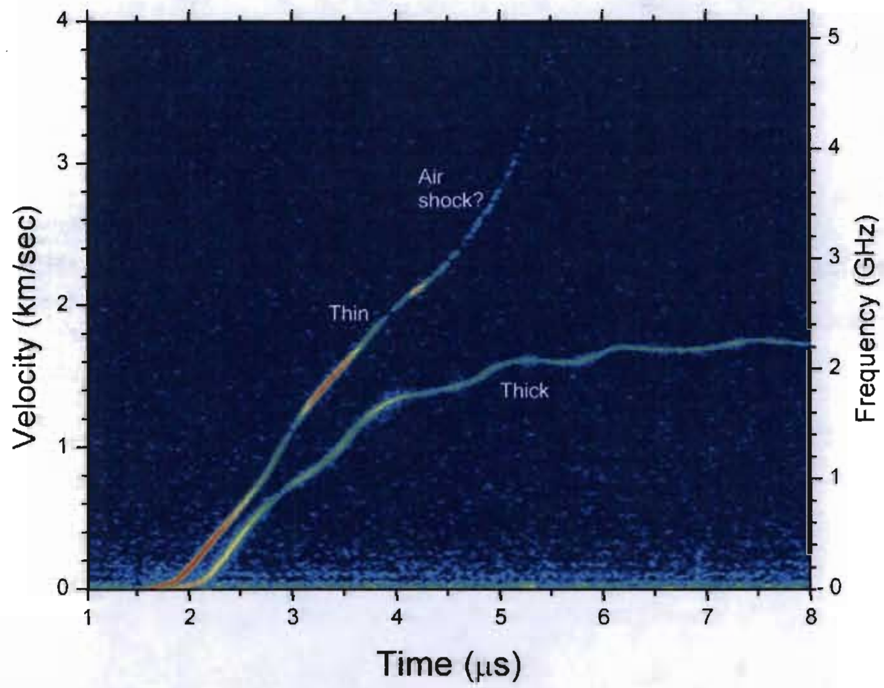
First shot proved we could do an experiment close to predictions



- **VISAR velocity from one of two copper samples, both nominally 125 mil x 10 mm**
  - *spICE* model (red) <u>appears</u> to under-predict surface velocity
  - But exact thickness and width not known to within 5%

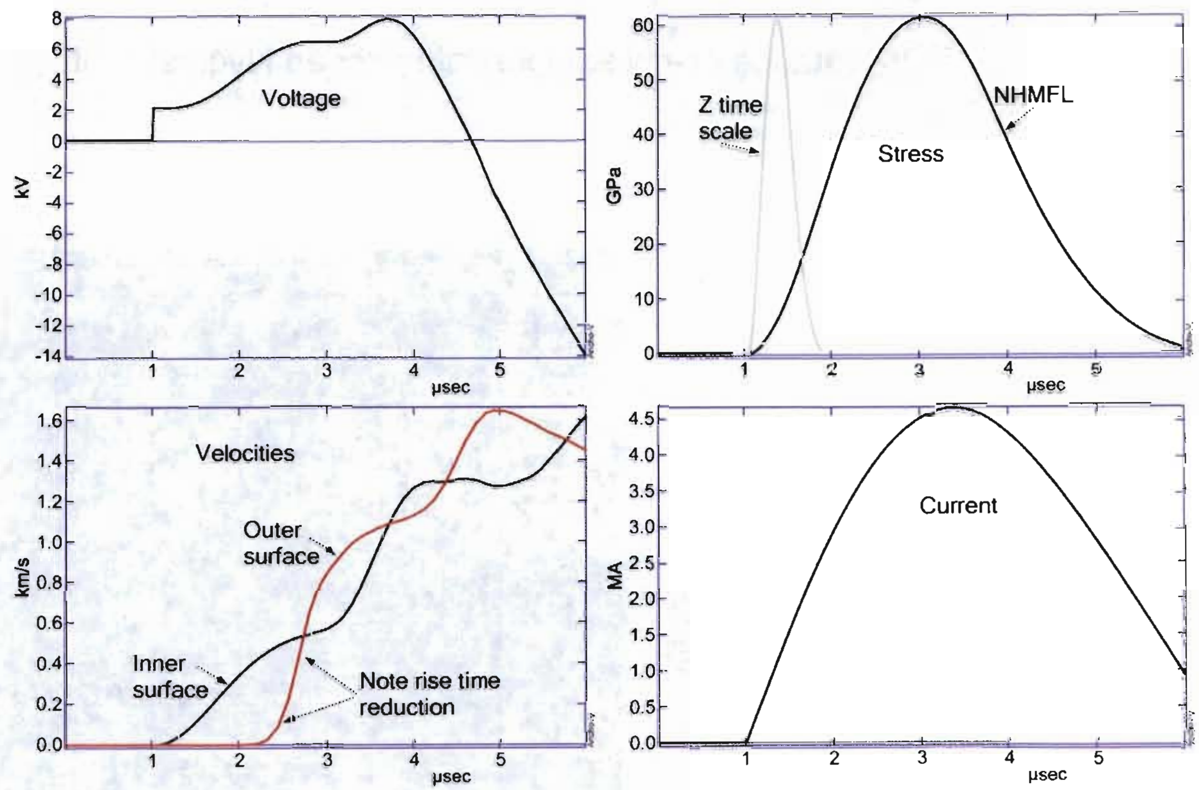
Experiments performed on copper

- **Samples, 77 and 125 mil, PDV diagnostics**
  - PDV data for 77-mil sample data exceed Nyquist limit (~3 GHz)



50 GPa experiments possible with present system

- splCE calculation for highest stress
  - Used EOS equivalent to SESAME
- Tungsten 5 mm thick x 10mm wide
- Bank voltage maximum - 60 kV
- P = 64.7 GPa peak
  - EOS portion ends at ~50 GPa
- Note reduction in surface velocity rise time does not approach shock conditions



Advantages of NHMFL-ICE system

- **Long rise time: Thicker samples possible, improves accuracy of measured stress *Δσ/σ***
  - Accuracy of metrology (*dh/h*) is improved
  - Accuracy of timing is improved, *Δt*
  - Minimizes inhomogeneity effects due to grain size
- **Long rise times mitigate against shock-up**
- **Long rise times lead to lower strain rates**
  - Bridges strain rate gap between Split Hopkinson Pressure Bar data 10^3/s and conventional ICE data (10^5/s to 10^6/s).
- **Economy**
  - Facility already exists – no capital outlay
  - Many experiments per day - reduces costs
  - Small staff
- **Portable**
  - Possible locations:
    - Nevada Test Site
    - MaRIE, the proposed LANL Matter-Radiation Interactions in Extremes facility
    - the LANL proton radiography facility
    - ANL Advanced Photon Source.

$$\frac{d\Delta\sigma}{\Delta\sigma} \approx \underbrace{\frac{dh}{h}}_{\text{Metrology}} + \underbrace{\frac{d\Delta u}{\Delta u}}_{\text{VISAR/ PDV}} + c_L(u)\underbrace{\frac{d\Delta t}{h}}_{\text{Timing}}$$

Conclusions

- The feasibility of NHMFL-ICE experiments has been demonstrated
- Modeled successfully with a hybrid electromechanical simulation using SESAME-equivalent EOS
- Sample dimensions determine the required rise time of the stress in the load which was shown to be approximately 2 μs
  - Significantly slower pulse rise time than Z - an advantage because:
    - It mitigates against shock-up and allows larger sample dimensions for higher accuracy
- Maximum stress ~50 GPa for present system
- Data bridges "strain rate gap" between 10^3/s and 10^6/s
- NHMFL-ICE technique would be an excellent complement to ongoing studies with gas guns